

Brief Announcement: Hierarchical Consensus

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1 Introduction

We introduce *Hierarchical Consensus*, an approach to generalize consensus that allows us to scale groups beyond a handful of nodes, across wide areas. Hierarchical Consensus (HC) increases the availability of consensus groups by partitioning the decision space and nominating distinct leaders for each partition. Partitions eliminate distance by allowing decisions to be co-located with replicas that are responding to accesses. Hierarchical consensus is flexible locally, but provides Hierarchical Consensus improves upon prior approaches [4, 2, 1, 5, 6, 3] by balancing load, allowing fast replication across wide areas, and enabling consensus across large (>100) systems of devices.

Our use case is that of maintaining *linearizability* across **read** and **update** operations used to support a wide-area object store or file system. We consider a set of processes $P = \{p_i\}_{i=1}^n$ which are connected via an asynchronous network, whose connections are highly variable. The variability of a communication link between p_i and p_j is modulated by the physical distance of the link across the geographic wide area. Each process maintains the state of a set of objects, $O = \{o_i^v\}_{i=1}^m$, which are accessed singly or in groups at a given process and whose state is represented by a monotonically increasing version number, v .

2 Hierarchical Consensus

Hierarchical consensus conducts coordination decisions as a tier of quorums such that parent quorums manage the decision space and leaf quorums manage access ordering. Hierarchical consensus considers the decision space as subsets of the object set, and subquorums are defined by a time-annotated disjoint subset of the objects they maintain, $Q_{i,e} \subset O$. The set of subquorums, Q is not a partition of O , but only represents the set of objects that are being accessed at time e .

The hierarchical consensus algorithm starts with a root quorum whose main responsibilities are i) the mapping of objects to subquorums and ii) the mapping of replicas to subquorums. Each instance of such a map defines a distinct *epoch*, E , a monotonically increasing representation of the term of Q_e . Decisions that require a change of the decision space or changes the mapping of objects or replicas to subquorums requires a new *epoch*. The fundamental relationship between epochs is as follows: any access that happens in epoch $E_i \rightarrow E_{i+1}$. Alternatively, any access in epoch E_{i+1} *depends on* all accesses in epoch E_i .

All accesses to an object must be forwarded to the leader of the subquorum that contains the object. Objects that are accessed together or who have application-specific, explicit dependencies (such as the set of objects included in a transaction) must be part of the same subquorum so that local accesses are totally ordered. Dependent objects that are not part of the same subquorum require either a change in epoch or a mechanism to allow *remote accesses*, which we will discuss in a following section. Accesses in different subquorums but in the same epoch happen concurrently from the global perspective (but are non-conflicting), though accesses in a specific subquorum are totally ordered locally.

2.1 Operation

The root consensus group coordinates all decision space changes. Consider the simple example of the transfer of object responsibility from one subquorum to another:

$$\begin{aligned}
Q_1 &: \{o_a, o_b, o_c\} \rightsquigarrow \{o_a, o_b, o_g, o_h\} \\
Q_2 &: \{o_d, o_e, o_f, o_g, o_h\} \rightsquigarrow \{o_c, o_d, o_e, o_f\}
\end{aligned}$$

Each of the two subquorums, Q_1 and Q_2 , wants to give up a portion of its existing decision space and to add objects currently mapped to another subquorum. Reallocating subquorums requires a two phase consensus decision. Both subquorum leaders send change requests to the leader of the parent quorum, which may aggregate several requests into a single namespace change. While the parent quorum gets consensus to make the epoch change, subquorums can continue operating on their own decision space. Once the parent quorum updates the epoch, it communicates the change to all affected subquorums. Each such subquorum then increments its epoch and acknowledges its change to the parent quorum. At this point, the subquorum can operate on the portion of the decision space it owned before, *but not the objects that are being added*. Once the parent quorum gets confirmations of epoch update from all subquorums, it notifies the subquorums that they can begin operating on the complete subset of objects from the new epoch.

2.2 Epochs and Ordering

Hierarchical consensus requires all accesses in all subquorums to be at least sequentially consistent. Local sequential consistency is guaranteed by serializing all accesses through a leader. Global sequential consistency is guaranteed by serializing epochs at the parent quorum.

Let *interval* i_n be the ordered set of accesses of the replicas in subquorum Q_i during epoch E_n . We enforce sequentially consistent ordering of all accesses in the entire system by ensuring that there must exist a total ordering of the intervals that produces the correct access results. Access results should be equivalent to any interval ordering such that all intervals in E_n occur before intervals in E_{n+1} (our “interval ordering” invariant). This is because there is no cross-traffic between any Q_i and Q_j , and therefore ordering interval i_n before j_n is exactly the same as ordering interval j_n before i_n , for any i, j , and n .

The internal invariant requires $\forall_{x,y} : Q_{x,i} \rightarrow Q_{y,i+1}$. Ordering all accesses according to consensus-based log order and interval order satisfies both the internal invariant and sequential consistency while still allowing subquorums to operate independently within epochs. Given Q_i and Q_j within epochs E_1 and E_2 , one possible interval order is $Q_{i,1} \rightarrow Q_{j,1} \rightarrow Q_{i,2} \rightarrow Q_{j,2}$.

2.2.1 Remote Accesses

By default we assume that the set of replicas *assigned* to subquorums are also disjoint, and that all accesses through a replica of a given subquorum are mapped to the local decision space. This is often reasonable. However, if an object is assigned to a decision space and another subquorum wishes to access it, the system must either disallow the access (our default approach) or take explicit notice that a dependency has been created between the subquorums.

The latter approach requires a serialization of all accesses currently within the remote quorum with respect to all accesses before the remote access in the local quorum. Assume a read access from Q_k to Q_i in epoch e ; at the time of the read all accesses in Q_i must \rightarrow all accesses following the read. We accommodate this requirement by using the read endpoints to break interval i_e into $i_{e,1}$ and $i_{e,2}$ at the point Q_i receives the remote access, and interval k_e into $k_{e,1}$ and $k_{e,2}$ at the point Q_k receives a response. Our results are consistent with total interval ordering by incorporating $Q_{i,1} \rightarrow Q_{i,2}$. Remote accesses are expensive and the runtime system must weigh the cost of repeated remote accesses against the cost of epoch changes.

2.2.2 Fuzzy Epochs

Only subquorums involved in decision space changes need take notice of epoch changes. Other subquorums can move to a new epoch at no cost when informed of new epoch numbers from

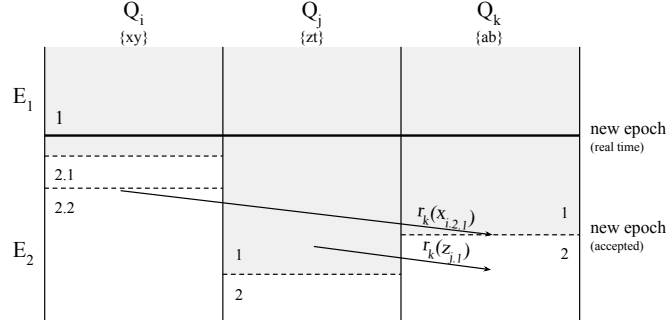


Figure 1: The gray region shows the “fuzzy” boundary between epochs E_1 and E_2 . The first read access, $r_k(x_{2.1})$, reads the value of object x from Q_i into Q_k and forces Q_k to change epochs.

remote requests. Slow-responding subquorums therefore do not block decision space changes for other quorums. Safety is guaranteed because no writes in the next epoch depend on these writes. These “fuzzy epochs” (Figure 1) allow an epoch change to be implemented solely by the root quorum, allowing subquorums to move to the new epoch independently. This flexibility is key to coping with partitions and varying connectivity in the wide area.

3 Correctness

We assert that consensus at the leaf nodes is correct and safe because decisions are implemented using well-known leader-oriented consensus approaches. Because decision allocation occurs on accesses and is defined by a fixed period of time, we propose to show correctness through *eventual quiescence*. Quiescence is the property that subquorums disband and return object ownership back to the parent quorum if activity ceases. Because all changes to the decision space require incrementing the epoch, if only the root quorum exists, the epoch is closed (e.g. no accesses will be applied to a log with that epoch).

The primary case to consider is an unsafe append to the access log: $Q_{i,e}$ appends object o_a^{v+1} while $Q_{j,e+1}$ appends object o_a^v (incorrectly specifying that $o_a^{v+1} \rightarrow o_a^v$). It is the parent quorum’s responsibility to ensure that $Q_{j,e+1}$ does not start operating until it has received confirmation from $Q_{i,e}$ that it has terminated. If the parent quorum does not receive a message from $Q_{i,e}$, it can enforce quiescence – closing epoch e , and then return control to $Q_{j,e+1}$. This causes all accesses in $Q_{i,e}$ to be dropped when it communicates with the leader.

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